Virtual Functional Segmentation of Snake Robots for Perception-Driven Obstacle-Aided Locomotion

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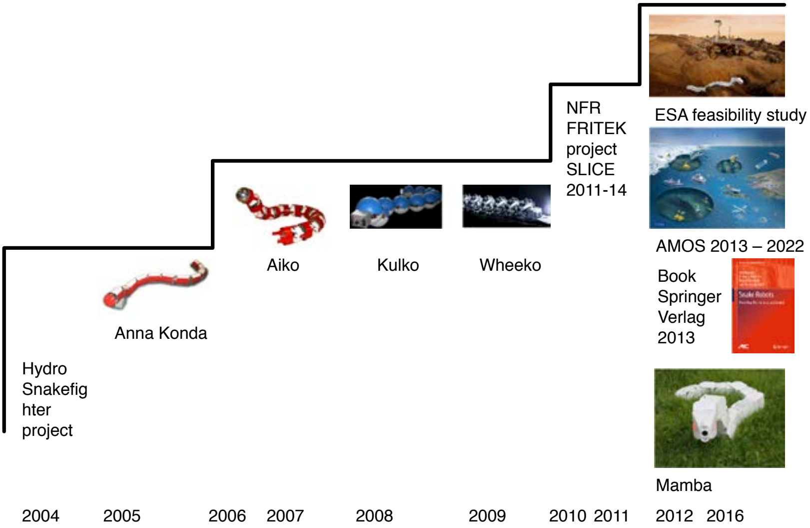
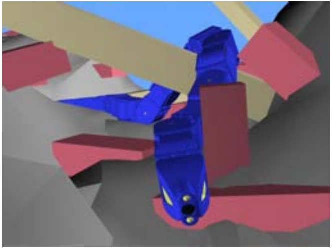
Summary

Biological snakes capabilities

Our research group



Bio-inspired robotic snakes



Building a robotic snake with such agility:

- different applications in challenging real-life operations, pipe inspection for oil and gas industry, fire-fighting operations and search-and-rescue.

***Obstacle-aided locomotion*:**

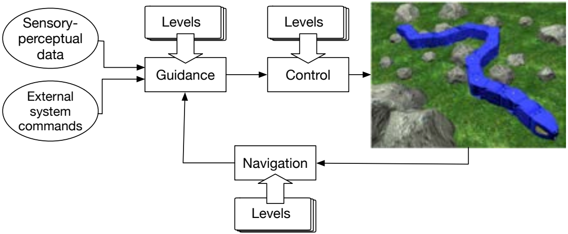
- snake robot locomotion in a cluttered environment where the snake robot utilises walls or external objects, other than the flat ground, for means of propulsion.

[1,2]

[1] A.A. Transeth et al. "Snake Robot Obstacle-Aided Locomotion: Modeling, Simulations, and Experiments". In: *IEEE Transactions on Robotics* 24.1 (Feb. 2008), pp. 88–104. ISSN: 1552-3098. DOI: 10.1109/TRO.2007.914849.

[2] Christian Holden, Øyvind Stavdahl, and Jan Tommy Gravdahl. "Optimal dynamic force mapping for obstacle-aided locomotion in 2D snake robots". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Chicago, Illinois, United States*. 2014, pp. 321–328.

Perception-driven obstacle-aided locomotion



Perception-driven obstacle-aided locomotion:

- locomotion where the snake robot utilises a sensory-perceptual system to perceive the surrounding operational environment, for means of propulsion.

[3,4]

[3] Filippo Sanfilippo et al. "Virtual functional segmentation of snake robots for perception-driven obstacle-aided locomotion". In: *Proc. of the IEEE Conference on Robotics and Biomimetics (ROBIO), Qingdao, China.* Manuscript accepted for publication. 2016.

[4] Filippo Sanfilippo et al. "Perception-driven obstacle-aided locomotion for snake robots: the state of the art, challenges and possibilities". In: *Journal of Intelligent & Robotic Systems, Springer* (2016). Manuscript submitted for publication.

Perception-driven obstacle-aided locomotion

Perception-driven obstacle-aided locomotion challenges:

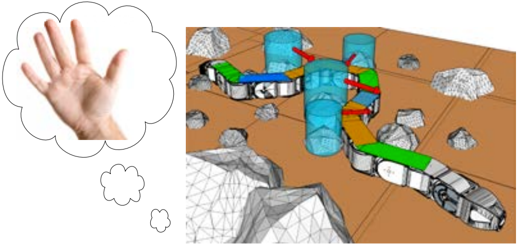
- snake robots are kinematically hyper-redundant robots;
- a high number of degrees of freedom is required to be controlled.

The greater part of existing literature considers motion across smooth, usually flat, surfaces. This can be attributed to the following main reasons[5]:

- most of the previous kinematic modelling techniques have not been particularly efficient or well suited to the needs of hyper-redundant robots;
- the mechanical design and control of snake robots as hyper-redundant robots has been perceived as unnecessarily complex;
- a model that suits the purpose of the interaction between the snake robot and the surrounding environment is still missing.

[5] G. S. Chirikjian and J. W. Burdick. "Hyper-redundant robot mechanisms and their applications". In: *Proc. of the IEEE/RSJ International Workshop on Intelligent Robots and Systems (IROS), Osaka, Japan*. Nov. 1991, 185–190 vol.1. DOI: 10.1109/IROS.1991.174447.

Underlying idea: *virtual functional segments* (VFS)

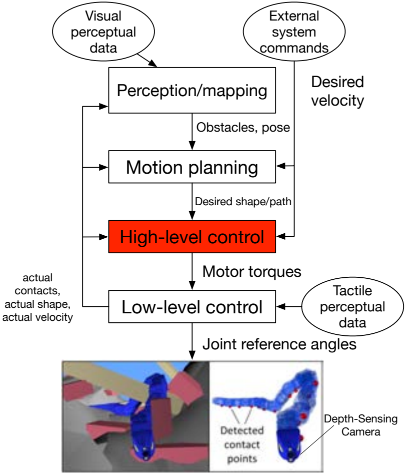


Contribution:

- simplifying the snake robot model to deal with a lower-dimensional system;
- a virtual partitioning of the snake in parameterised *virtual functional segments* (VFS) is proposed inspired by the concept of *virtual constraints* (VC)[6];
- model the snake robot body with a chain of continuous curves (named parametrised *virtual functional segments*) (VFS) with the fewest possible parameters.

[6] Carlos Canudas-de Wit. "On the concept of virtual constraints as a tool for walking robot control and balancing". In: *Annual Reviews in Control* 28.2 (2004), pp. 157–166. ISSN: 1367-5788. DOI: 10.1016/j.arcontrol.2004.03.

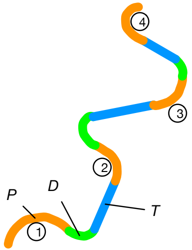
A hierarchical control framework



High-level control:

- mapping a desired parameterised path to obstacle contact forces, and these forces to control inputs for the joint actuators, given a desired robot velocity;
- the inputs are the desired robot shape, the desired robot velocity and the actual contacts;
- the expected output consists of motor torques for the joint actuators that are used as thrusters, while joint reference angles are provided to the joint actuators that are position-controlled.

Virtual functional segment (VFS) parametrisation



Assumptions:

- the snake robot moves in 2D;
- the robot has infinite, infinitely short links, so that it can be considered as a continuous curve.

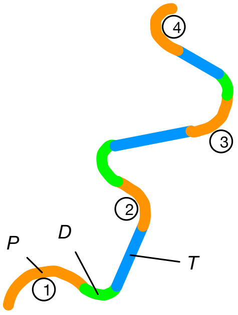
Virtual functional segment (VFS):

- a coherent section of the snake robot;
- a VFS may extend over any number of physical links but it may not overlap with other VFS;
- each joint of the snake robot belongs to exactly one VFS at a time.

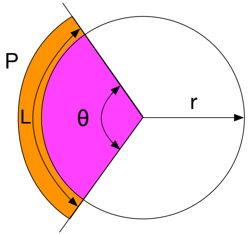
Three distinct classes of VFS:

- *propulsive*, P;
- *directive*, D;
- *transport*, T.

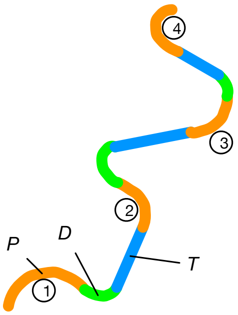
Propulsive VFS



- Each of *P* VFS represents a section of the snake that pushes against an obstacle to provide forward propulsion.
- *P* VFS can be parametrised with two parameters: the curvature radius, r, and the subtended angle, θ, (i.e. the VFS forms a circular arc determined by these parameters).

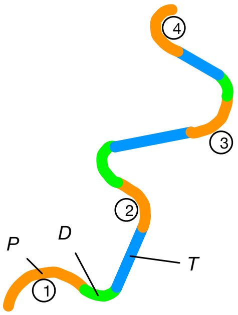


Directive VFS



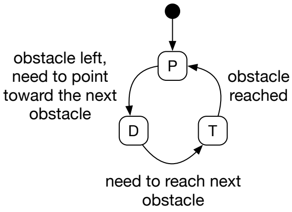
- A *D* VFS follows each *P* VFS.
- The sole purpose of *D* VFS is to "point toward" the beginning of the next *P* VFS, so that the next section, *T*, can be completely straight.
- Each *D* VFS splices together a *P* and a *T* VFS.
- *D* VFS are characterised by only one parameter, namely the angle of curvature, θ_d.
- The control idea is to have a minimum radius of curvature, R_d, so that we "consume" the least amount of snake length for this segment.

Transport VFS



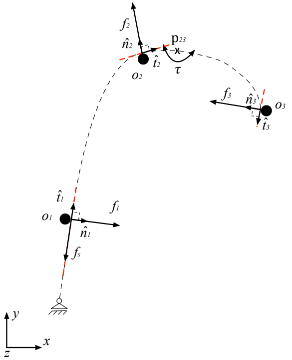
- Each T VFS is a section of the snake body, which is located between a D VFS and the previous P VFS, forming a straight line with one parameter, the length, l.

VFS state transition



- Sparse obstacle distribution with a low spatial density.
- Once the snake robot body reaches some obstacles, each robot joint which is part of a section that curves around an obstacle belongs to a *P* VFS.
- When the obstacle is left and it is necessary to point toward the next obstacle, then a discrete transition is executed for each joint from a *P* VFS to a *D* VFS.
- Once the direction toward the next obstacle is set, then a discrete transition is executed for each joint from a *D* VFS to a *T* VFS.
- When the next obstacle is reached, a discrete transition is executed for each joint from a *T* VFS, to a *P* VFS.

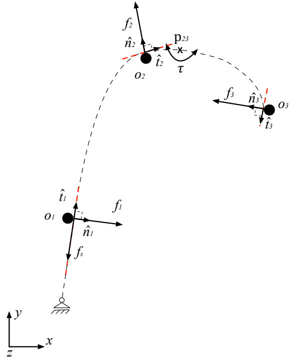
The obstacle triplet model



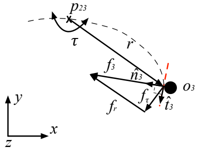
Based on the foundations proposed in [7]. The aim is to reduce the problem from a multi-dimensional problem to a two-dimensional problem (along the path, across the path).

1. $S(s)$ is known. o_1, o_2, o_3, are also known;
2. the snake is always on the path $S(s)$;
3. the snake is planar;
4. the snake is continuous;
5. there is no ground or obstacle friction;
6. the snake is at rest;
7. the snake tail link is tethered to the ground. A tensile force, f_s, acts along the tangent at o_1;
8. the snake is perfectly rigid except at the point where an internal torque can be applied;
9. τ is applied at a known point, p_{23}, on the path (i.e. snake) between o_2 and o_3.

The obstacle triplet model



The torque τ makes the snake straighten. This produces a counter force, f_τ, acting at the obstacle o_3.



$$f_3 \cdot \hat{t}_3 = 0. \tag{1}$$

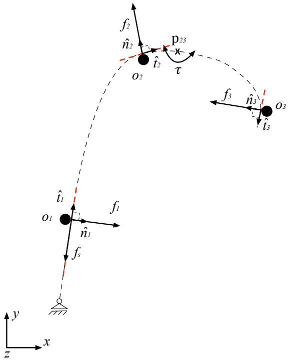
$$f_3 = f_\tau + f_r, \tag{2}$$

$$f_\tau = r \times \tau, \tag{3}$$

while f_r is the force component parallel to the torque radius, r, and by definition can be expressed as:

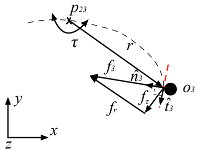
$$f_r \triangleq |f_r| \frac{r}{|r|}. \tag{4}$$

The obstacle triplet model



By combining (2), (3) and (4):

$$f_3 = r \times \tau + |f_r|\frac{r}{|r|}, \qquad (5)$$



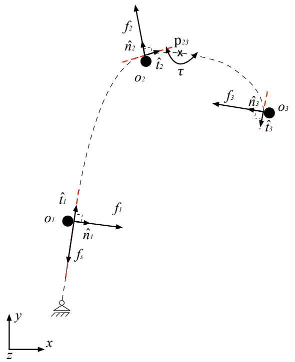
which, because of (1), can be rewritten as:

$$(r \times \tau + |f_r|\frac{r}{|r|}) \cdot \hat{t}_3 = 0. \qquad (6)$$

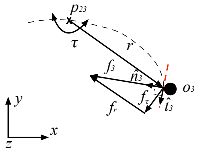
Distributive prop. of $\cdot$ and the anticommutative prop. of the $\times$:

$$|f_r|\frac{r}{|r|} \cdot \hat{t}_3 = (\tau \times r) \cdot \hat{t}_3. \qquad (7)$$

The obstacle triplet model



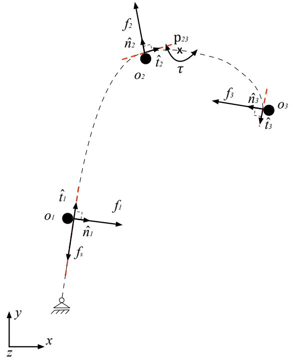
$$|f_r| = \frac{(\tau \times r) \cdot \hat{t}_3}{\frac{r}{|r|} \cdot \hat{t}_3}. \qquad (8)$$



Consequently, because of (5) and (8), f_3 can be rewritten as:

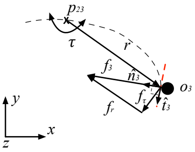
$$f_3 = r \times \tau + \left[\frac{(\tau \times r) \cdot \hat{t}_3}{\frac{r}{|r|} \cdot \hat{t}_3} \right] \frac{r}{|r|}. \qquad (9)$$

The obstacle triplet model



Because of assumption 6 (static conditions):

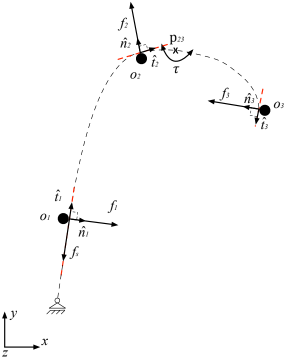
$$f_s + f_1 + f_2 + f_3 = 0, \qquad (10)$$



where, f_s is the tensile force that need to be counterbalanced, f_3 is given by (9), while f_1, f_2 are unknown variables.
To obtain another relevant equation, the torques exerted on the robot about the global origin by the external forces can be considered as follows:

$$o_1 \times (f_s + f_1) + o_2 \times f_2 + o_3 \times f_3 = 0. \quad (11)$$

The obstacle triplet model



τ can be uniquely computed at any point. Given any point, s, on the path, it is possible to uniquely express the bending torque as a function of f_s, f_1, f_2, f_3:

$$\tau(s) = f(f_s, f_1, f_2, f_3). \qquad (12)$$

Equivalently, f_s, can be obtained as a function of $\tau(s), f_1, f_2, f_3$:

$$f_s = g(\tau(s), f_1, f_2, f_3). \qquad (13)$$

Remark:

For an obstacle triplet model (3 contact points), only one control variable, $\tau(s)$, is needed to achieve obstacle-aided locomotion. The torque, $\tau(s)$, can be applied at any point and it can be seen as a thruster for the snake robot.

The obstacle triplet model

Conclusion and future work

Contribution:

- a simplified snake robot model with the aim of establishing the foundation elements of *perception-driven obstacle-aided locomotion*;
- virtual partitioning of the snake into parameterised *virtual functional segments* (VFS);
- for the *obstacle triplet model*, only one control variable for the torque is needed to achieve *obstacle-aided locomotion*.

Future work:

- validation, i.e. in simulation and/or physical experiments;
- extend the *obstacle triplet model* to *n* obstacles, to consider friction and to extend the model to a three-dimensional case;
- the case of not having alternating sites for the obstacles must also be considered in the future.

Thank you for your attention

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[7] Christian Holden and Øyvind Stavdahl. "Optimal static propulsive force for obstacle-aided locomotion in snake robots". In: *Proc. of the IEEE International Conference on Robotics and Biomimetics (ROBIO), Shenzhen, China*. 2013, pp. 1125–1130.